



Green Concrete Roads with Geo-Polymer Concrete: A Review

V.D. Shinde¹, N. K. Patil², D. M. Shinde³

¹Assistant Professor, Civil Engineering Department, Govt. College of Engineering, Karad, India.

²Professor, Civil Engineering Department, Sanjay Ghodawat College of Engineering and Technology, Atigre, Kolhapur, India.

³Practicing Civil and Structural Engineer, India.

Emails: vaishali.bogar@gcekarad.ac.in¹, ndkumar.patil@sanjayghodawatuniversity.ac.in², shinde.dm@gmail.com³

Abstract

Concrete is the most widely used man-made material for construction across the globe. As a composite material, it binds inert aggregates such as sand and gravel with cement to produce strong, economical, and versatile building material. In India, cement production has already reached 450 million metric tons and is projected to grow at a rate of 8–9% annually. With the rapid expansion of infrastructure, more than 40% of this cement is consumed in concrete pavement construction. However, the production of ordinary Portland cement (OPC) releases nearly an equivalent mass of carbon dioxide into the atmosphere, contributing significantly to greenhouse gas emissions. Simultaneously, the country's dependence on coal and lignite for thermal power generation results in the generation of large quantities of fly ash, as Indian coal typically contains 24–63% as compared to 3–20% in imported coal. Currently, fly ash production in India has reached 147 million metric tons per year, creating enormous challenges for disposal, land management, and air and water pollution. These pressing environmental concerns underscore the urgent need for sustainable alternatives to OPC-based concrete. Geopolymer concrete has emerged as one such promising solution. By utilizing fly ash, which is rich in silica and alumina, and activating it with alkaline chemicals, geopolymer concrete forms an aluminon-silicate gel that serves as the binding phase, eliminating the need for OPC or large amounts of water. This approach not only converts industrial waste into a valuable construction material but also produces concrete with strength comparable to conventional concrete. The present study reviews the potential of geopolymer concrete as both an alternative to OPC-based concrete and as a feasible option for large-scale applications such as pavement-quality concrete.

Keywords: Geo-polymer Concrete, Fly Ash, strength, Pavement Quality Concrete.

1. Introduction

The increasing demand for cement in the construction industry has raised serious concerns about sustainability and environmental impacts. India alone produces nearly 850 million tons of ordinary Portland cement (OPC) annually, with a growth rate of 7–8%, making it one of the largest contributors to global CO₂ emissions [1]. The production of OPC is energy-intensive, releasing nearly one ton of CO₂ per tons of cement manufactured [2,3]. Consequently, researchers have focused on supplementary cementitious materials and alternative binders to mitigate carbon emissions and reduce dependence on natural resources [4]. Among the promising alternatives, geopolymer concrete has gained significant attention due to its ability to utilize

industrial by-products such as fly ash and slag as precursors, activated by alkaline solutions [3,5,6]. Class F fly ash, abundantly available as an industrial waste in India, has been identified as a sustainable material for geopolymer concrete, offering reduced carbon footprint and efficient waste management [4,7,8]. While many studies have demonstrated its potential to achieve adequate strength [9–12], the long-term durability of geopolymer concrete remains a critical concern for field applications [7,13]. Durability issues such as resistance to chemical attack, elevated temperature, and long-term performance under environmental exposure have been widely studied, but results indicate significant variability depending on mix design, curing regime,

and activator concentration [6,7,10,12]. For instance, Amran et al. [7] emphasized that although geopolymer concretes show superior resistance to chloride penetration and sulphate attack compared to OPC, their durability performance is highly mix-dependent. Similarly, Tayeh et al. [5] reported changes in mechanical properties at elevated temperatures, while Nurrudin et al. [13] highlighted the importance of curing methods in achieving stable durability outcomes. Given this background, the present research investigates the durability properties of geopolymer concrete prepared with 100% replacement of cement using Class F fly ash and activated with sodium hydroxide and sodium silicate solutions of 13 M concentration. The experimental program focuses on M40 grade concrete, aiming to verify whether geopolymer concrete can provide a reliable and sustainable alternative to conventional OPC-based systems, especially with respect to long-term durability performance.

2. Necessity Of Geo-Polymer Concrete

Geopolymer concrete was first introduced by Joseph Davidovits in 1978 as a novel binder derived from inorganic polymerization [2]. It can be synthesized from natural aluminon-silicate sources such as meta kaolinite or industrial by-products like fly ash and slag, which are rich in silica (Si) and alumina (Al) [3], [4]. When these materials are activated by an alkaline solution, typically a combination of sodium hydroxide and sodium silicate, the dissolution of Si and Al initiates a polymerization reaction that forms long molecular chains and a hardened binder matrix [6], [12]. This process produces a three-dimensional polymeric network of Si–O–Al–O bonds, which are structurally analogous to the calcium–silicate–hydrate (C–S–H) gel present in conventional Portland cement concrete [5], [7], [11]. Consequently, geopolymer concrete has emerged as a sustainable alternative to ordinary cement-based systems, offering potential for enhanced durability and reduced environmental impact [1], [2], [8].

3. Constituents of Geo-Polymer Concrete Concrete

- Geopolymer concrete is increasingly recognized as a sustainable alternative to conventional Portland cement concrete,

primarily due to its utilization of industrial by-products as raw materials and its reduced environmental footprint [1], [2]. The essential constituents of geopolymer concrete include fly ash and alkaline activators, which together form a durable aluminon-silicate binder.

- **Fly Ash:** Fly ash, a fine powder generated as a by-product of coal combustion in thermal power plants, is rich in silica (SiO_2) and alumina (Al_2O_3) [3], [4]. In geopolymer concrete, it acts as the principal source of aluminon-silicate material. When exposed to alkaline solutions, fly ash undergoes dissolution and subsequent polymerization, forming a binding gel that performs a role like that of cement in traditional concrete [5], [6]. The incorporation of fly ash not only minimizes the need for landfill disposal but also reduces greenhouse gas emissions linked to cement production, while enhancing strength and durability properties of concrete [7], [8].
- **Alkaline Activators:** Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) Sodium hydroxide and potassium hydroxide are strong alkalis with high solubility in water [9]. These activators play a critical role in dissolving the silica and alumina phases of fly ash, enabling the formation of polymeric chains and a hardened binder matrix [10]. However, due to their high alkalinity, they pose significant safety hazards, including risks of burns, and thus require careful handling during mixing and application [11].
- **Alkaline Activators:** Sodium Silicate or Potassium Silicate Sodium silicate (Na_2SiO_3) and potassium silicate are commonly used in conjunction with hydroxides to further improve the geo polymerization process [12]. They provide an additional source of silica, which enhances the polymer network and results in improved cohesion and durability of the binder [13]. The inclusion of these silicate solutions has been reported to significantly improve compressive strength and chemical resistance, thereby broadening the

applicability of geopolymer concrete in structural engineering [14], [15].

4. Chemistry of Geo-polymer Concrete

As per American Society for Testing and Materials (ASTM C618-92a, 1994), Fly ash is classified into two types:

- Class F. Fly ash products in this group have pozzolanic properties and are characterized by $SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$; (b) $SO_3 < 5\%$; (c) moisture content $< 3\%$; and (d) loss on ignition (LOI) $< 6\%$.
- Class C. Fly ash products in this group have combinations of $SiO_2 + Al_2O_3 + Fe_2O_3 < 70\%$. Class C fly ash shows cementations properties and is characterized by (a) $SiO_2 + Al_2O_3 + Fe_2O_3 < 70\%$ due to high Ca

and Mg contents (27 and 3.8%, respectively).

4.1. Chemical Reactions Involved in Fly Ash-Based Geo-polymer Concretes

When fly ash is mixed with an alkali activator such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) to form a Geo-polymer Concrete, several chemical reactions occur. These reactions lead to the formation of a three-dimensional network structure known as a Geo-polymer Concrete binder. Here's a detailed look at the chemical reactions involved in the hydration process for vitreous silica with a $pH > 12$ are:

4.1.1. Dissolution of Silica and Alumina

Silica Dissolution: ** NaOH or KOH reacts with the amorphous silica (SiO_2) present in fly ash to form silicate ions ($Si(OH)_4^-$) in solution Shown in Table 1

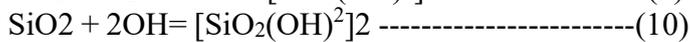
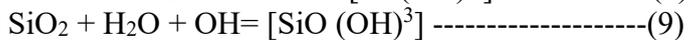
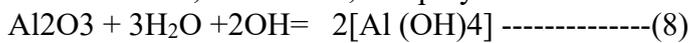
Table 1 Fly Ash Dissolution & Gel Formation

Dissolution of Silica and Alumina: Silica Dissolution: ** NaOH or KOH reacts with the amorphous silica (SiO_2) present in fly ash to form silicate ions ($Si(OH)_4^-$) in solution			
1	$SiO_2 + 2OH^- = SiO_3 + H_2O$	Silica action	----- 1
2	$Al_2O_3 + 2OH^- = 2AlO_2 + H_2O$	Alumina Al_2O_3 -	----- 2
3	$CaO + H_2O = Ca_2 + 2OH^-$	CaO and MgO reaction	----- 3
4	$Na_2O + H_2O = 2Na^+ + 2OH^-$	Na_2O and K_2O reaction	----- 4
5	$Fe_2O_3 + 3H_2O = 2Fe^{3+} + 6OH^-$	Fe_2O_3 reacts	----- 5
6	$TiO_2 + OH^- = HTiO_3^-$	TiO_2 hydrates	----- 6
The reaction of the fly ash glass is proposed as follows: Polymerization and Gel Formation: Silicate ions ($Si(OH)_4^-$) and aluminate ions ($Al(OH)_4^-$) polymerize to form a three-dimensional network of silicon-oxygen (Si-O) and aluminum-oxygen (Al-O) bonds			
7	$SiO_2 \cdot \alpha Al_2O_3 \cdot \beta CaO \cdot \gamma Na_2O \cdot \delta Fe_2O_3 \cdot \epsilon TiO_2 + (\beta + \gamma + 3\delta) H_2O + (2 + 2\alpha + \epsilon) OH^- = SiO_3 + 2\alpha AlO_2 + \beta Ca_2 + 2\gamma Na^+ + 2\delta Fe^{3+} + \epsilon HTiO_3^- + (1 + \alpha) H_2O + 2(\beta + \gamma + 3\delta) -----$ $-(7)$		

The reaction of the fly ash glass is proposed as follows: Polymerization and Gel Formation: Silicate ions ($Si(OH)_4^-$) and aluminate ions ($Al(OH)_4^-$) polymerize to form a three-dimensional network of silicon-oxygen (Si-O) and aluminum-oxygen (Al-O) bonds

$TiO_2 + (\beta + \gamma + 3\delta) H_2O + (2 + 2\alpha + \epsilon) OH^- = SiO_3 + 2\alpha AlO_2 + \beta Ca_2 + 2\gamma Na^+ + 2\delta Fe^{3+} + \epsilon HTiO_3^- + (1 + \alpha) H_2O + 2(\beta + \gamma + 3\delta) ----- (7)$. Reactions 1-7 show that Silica, Aluminum-oxide and Titanium oxide consume hydroxides, whereas the Earth alkalis (CaO, MgO), alkalis (Na₂O, K₂O), and iron oxide produce

hydroxides. Fly ash contains high percentage of amorphous alumina and silica that make it very suitable for making Geo-polymer Concretes. After fly ash is mixed with an alkaline solution, dissolution of silicate species begins. The type and concentration of alkali solution affect the dissolution of fly ash. It was seen leaching of Al^{3+} and Si^{4+} ions was generally high with sodium hydroxide solution compared to potassium hydroxide solution. There are three steps involved in Geo-polymer Concrete polymerization i.e., dissolution of Al and Si in the alkali medium, orientation, and poly-condensation.



In mixtures that have low Si/Al ratios (approximately 1), condensation occurs predominantly between aluminate and silicate species resulting in poly (isolate) polymer structures. These are the backbone structures of bricks and ceramics. However, when the Si/Al ratio increases (> 1), the silicate species tends to condense among themselves to form oligomeric silicates. Then, these oligomeric silicates condense with $Al(OH)_4^-$, forming a rigid 3D network of polymer structures, poly(sialate-siloxo) and poly (Sialate-Disiloxo). Aluminosilicate Geo-polymer Concretes with SiO_2/Al_2O_3 ratios more than 1 have been studied and found that for H_2O/Na_2O ratio 12, provide good workability Geo-polymer Concretes. Better strength properties are reported for mixtures with SiO_2/Al_2O_3 ratios in the range of 3.4 – 3.8, with an Na_2O/Al_2O_3 ratio of about 11 be better.

5. Advantages of Geo-polymer Concrete

- **High Compressive Strength and Durability:** Geo-polymer Concrete exhibit impressive compressive strength and durability, often matching or exceeding that of traditional Portland cement concrete. This makes them suitable for a variety of structural applications where strength and longevity are critical.
- **Chemical Resistance:** These materials are highly resistant to chemical attacks, such as sulfate attacks and alkali-silica reaction. This resistance enhances the lifespan and reliability of structures built with Geo-polymer Concrete, especially in harsh

chemical environments.

- **Lower Carbon Footprint:** The production of Geo-polymer Concretes requires less energy compared to Portland cement, resulting in a significantly lower carbon footprint. This reduction in energy use means fewer carbon dioxide emissions, making Geo-polymer Concretes a more environmentally friendly alternative.

6. Applications of Geo-polymer Concretes

- **Construction Materials:** Geo-polymer Concretes are utilized as binders in the production of concrete, mortars, and grouts for various construction purposes. These materials provide the necessary bonding and strength for building structures, paving, and other general construction activities.
- **Specialized Applications:** Due to their high strength, durability, and chemical resistance, Geo-polymer Concretes are ideal for high-performance applications. They are particularly suitable for use in marine environments, where structures are exposed to harsh chemical conditions, and for infrastructure repair, where longevity and robustness are critical.

7. Limitations of Geo-polymer Concrete

- **Transporting Fly Ash:** One significant limitation is the challenge of transporting fly ash, a key base material for Geo-polymer Concrete, to the required locations. The logistics involved in moving large quantities of fly ash can be complex and costly, especially if the production site is far from the source of fly ash.
- **High Cost of Alkaline Solution:** The alkaline solutions used to activate the Geo-polymer Concrete polymerization process are often expensive. These costs can add up, making the overall production of Geo-polymer Concrete more costly compared to traditional Portland cement concrete.
- **Safety Risks:** The high alkalinity of the activating solutions poses safety risks. Handling and storing these solutions require careful safety measures to prevent accidents,



which can add to the complexity and cost of using Geo-polymer Concrete.

- **Steam/High-Temperature Curing:** Geo polymer Concrete often requires steam curing or high-temperature curing processes to achieve optimal properties. Implementing these curing processes in practical applications can be difficult, particularly for large-scale or on-site construction projects, where maintaining controlled temperature conditions is challenging.

7.1. Ongoing Research

Considerable research is being conducted to overcome these technical hurdles. Scientists and engineers are exploring alternative materials, cost-effective production methods, and safer handling practices. Innovations in curing techniques, such as ambient temperature curing, are also being investigated to make Geo-polymer Concrete more practical and accessible for widespread use. This ongoing research aims to refine Geo-polymer Concrete systems, enhancing their viability as sustainable construction material.

8. Related works for use of Geo-polymer Concrete for road pavement projects

Geo-polymer Concrete, an innovative and eco-friendly material, has seen successful applications in road pavement projects both nationally and internationally, serving as a full replacement for conventional concrete.

8.1. National Example: India

In India, a notable application of Geo-polymer Concrete for road pavements is seen in various infrastructure projects aimed at reducing the carbon footprint. Researchers and engineers have successfully demonstrated its use in several pilot projects, proving its durability and environmental benefits. This shift towards using industrial byproducts like fly ash and ground granulated blast furnace slag (GGBS) significantly reduces the reliance on traditional Portland cement, thereby lowering carbon emissions associated with cement production.

8.2. International Example: Australia

Australia has been at the forefront of Geo-polymer Concrete technology. The Global Change Institute at

the University of Queensland constructed the world's first Geo-polymer Concrete building. Additionally, several road pavement projects have employed Geo-polymer Concrete, showcasing its robustness and resilience in demanding environments. The successful use of Geo-polymer Concrete in Australia's infrastructure projects highlights its potential as a sustainable alternative to traditional concrete. These examples underscore the practical benefits of Geo-polymer Concrete in reducing environmental impact while maintaining the strength and durability required for road pavements.

Conclusion

User-friendly Geo-polymer Concrete can be utilized in conditions like those suitable for ordinary Portland cement concrete. The components of Geo-polymer Concrete should be able to mix with a relatively low alkali activating solution and cure in a reasonable time under ambient conditions. The production of versatile and cost-effective Geo-polymer Concrete can be achieved with mixing and hardening processes like those of Portland cement. This makes Geo-polymer Concrete a viable option for repairs and rehabilitation projects. Due to its high early strength, Geo-polymer Concrete is highly effective in the precast industry, allowing for large-scale production in a short duration and minimizing breakage during transportation. It is also suitable for use in beam-column junctions of reinforced concrete structures and various infrastructure works. Additionally, the utilization of fly ash in Geo-polymer Concrete eliminates the need for landfills to dispose of this industrial byproduct. The Government can take necessary steps to extract sodium hydroxide and sodium silicate solutions from waste materials of chemical industries, thereby reducing the cost of alkaline solutions required for Geo-polymer Concrete production. This initiative can further enhance the economic feasibility and environmental benefits of using Geo-polymer Concrete in construction. By embracing these measures, the construction industry can significantly reduce its environmental impact while maintaining the strength and durability of conventional concrete solutions.

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